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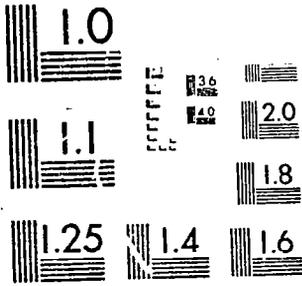
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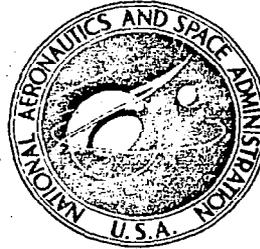
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# APPLICATIONS OF AEROSPACE TECHNOLOGY

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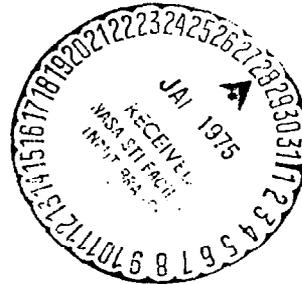
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## HEAT PIPES

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*for Technology Utilization Office*



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HEAT PIPES

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## INTRODUCTION

How does new knowledge, acquired for one purpose, develop into useful technology having significant impact and benefits to society? This is one case study in a series of detailed investigations tracing the origins of new knowledge developed to solve specific problems of manned space exploration, and its subsequent modification and application to commercial needs.

What differences exist between the technology required for space exploration and the requirements for application to earthly problems? What factors determine the time required to convert new knowledge into viable economic benefits? Various case examples disclose differing patterns of technological development. By comparing the common and contrasting findings it may be possible to understand better how new knowledge generates real benefits.

Starting from a specific "knowledge contribution" previously identified from an analysis of astronaut life support requirements, the origins, adaptations, and eventual significance of the new technology are presented.

## HEAT PIPES

### Knowledge Contribution Previously Identified

Vapor chamber heat transfer systems using capillary wick pumping had been investigated for thermal control of spacecraft.

As soon as the modern heat pipe was described, space scientists adapted the principle to the cooling of space suits. Metabolic heat could be transferred through the walls of pressure suits and into space. Several innovations were achieved: A controllable heat pipe or "thermal switch" was devised, permitting heat flow to be regulated; flexible heat pipes were developed to maintain contact with the astronaut's skin, yet permit normal body movement inside "hard" suits. Heat pipe wick materials and performance were improved, and techniques were devised to prevent freeze-up of the heat transfer fluid, and permit restarting of heat pipes after solidification of the working fluid.

NASA scientists indicated that controllable heat pipes, and designs for automatically maintaining a selected constant temperature would add significantly to the versatility and usefulness of heat pipes in industrial processing, manufacture of integrated circuits, and in temperature stabilization of electronics.

### I. What They Are

The heat pipe is a high-performance heat transfer device, able to transfer heat at high rates, over considerable distances, with almost no temperature drop. The principle of the heat pipe is an amazingly simple one. In its basic form, the heat pipe consists of a sealed tube, lined with a porous capillary wick that is saturated with a volatile fluid as shown in Figure 1. Heat absorbed by the evaporator zone at one end, vaporizes the fluid; vapor flows to the other end where it condenses, giving up heat. The condensed liquid then flows back through the wick to the evaporator.

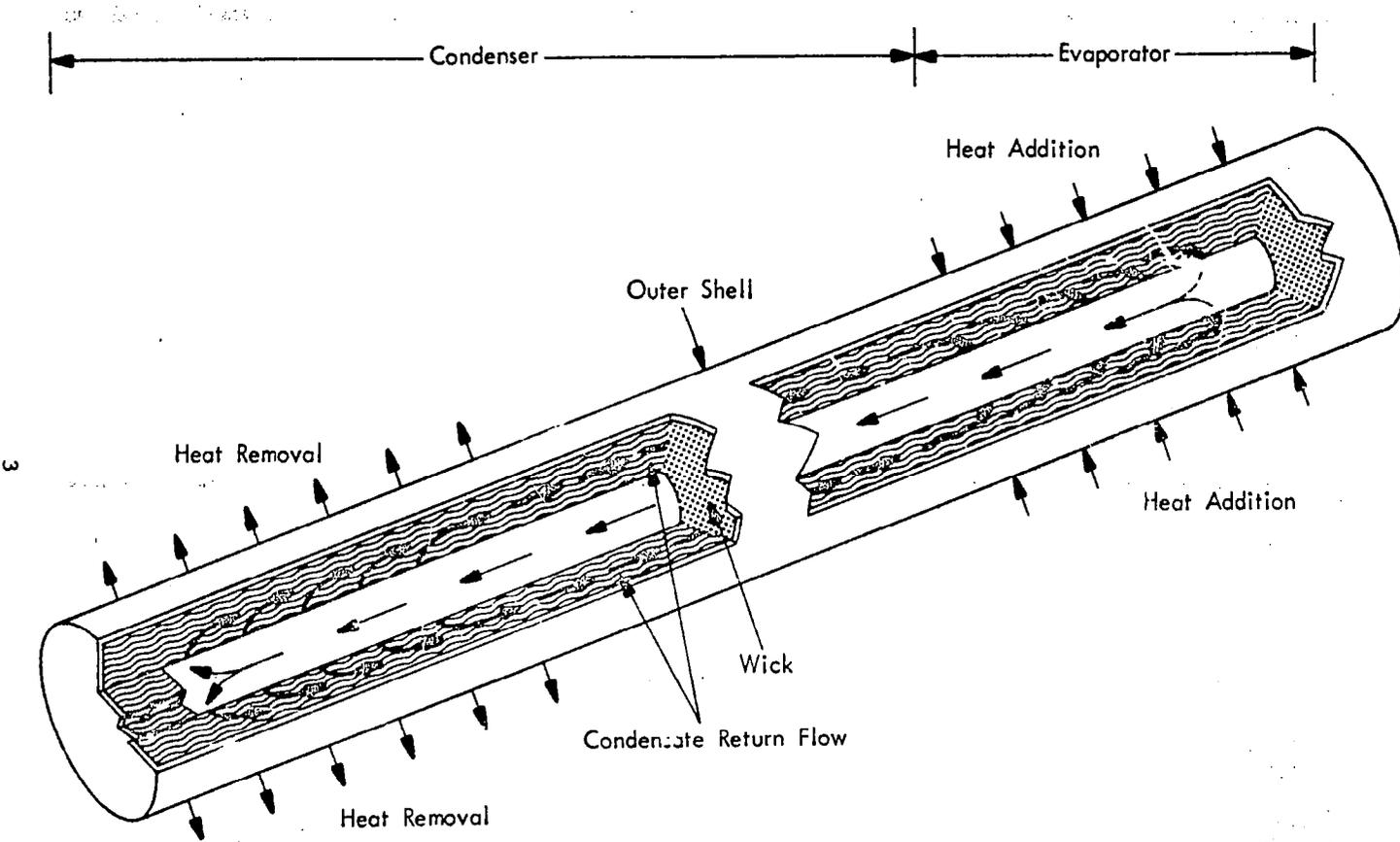


Figure 1 - Parts and Functions of the Basic Heat Pipe

The heat pipe has been called a thermal "superconductor"--since it can transfer 500 to 1,000 times as much heat as a solid copper conductor of the same size. By using various fluids, heat pipes have been designed to operate at temperatures from glowing incandescence at 3500° F, down to the ultracold, cryogenic region.

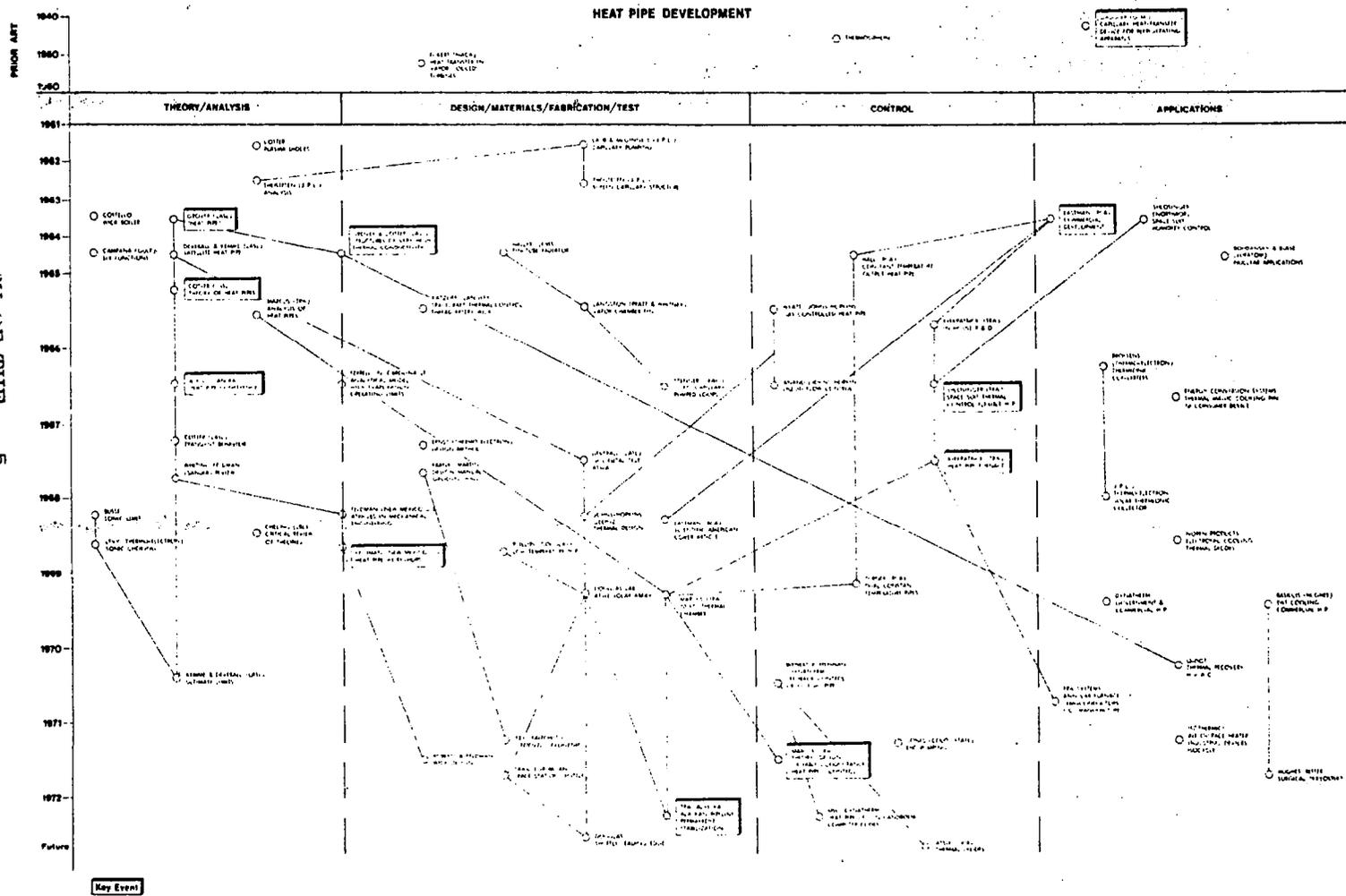
Any device that can heat or cool with high efficiency, yet has no moving parts, is completely self-contained, does not rely on gravity, and has extremely fast response time, is ideally suited for thermal control in space--where it has been widely used. Today, heat pipes are also used in scores of ways on earth--in air conditioning, industrial processes, nuclear power generators, electric motors, automobile engines, hot water heaters, and in the roasting of meats. It is particularly significant that uses virtually unrecognized 10 years ago comprise today's most important and rapidly growing areas of application: energy conservation, protecting the environment, manufacturing integrated circuits, reducing noise pollution, and cryosurgery.

## II. Development History of Heat Pipes

In retrospect, the development of heat pipe technology exhibits many of the characteristics which typify other technical advances. Yet the pattern of development shows several distinguishing characteristics which set it apart from the progression that typifies transformation of new knowledge into economic and social benefits. The most important differences are due to a lack of historical roots--there was no equivalent earlier technology. The heat pipe concept introduced basically new functions and effects, and was not simply an improvement on earlier heat transfer technology. Radical innovations thread a more difficult maze toward widespread applications.

The major discoveries and principal pathways of research in heat pipe development are shown in Figure 2. Key events of major significance, which influenced subsequent development and application of heat pipes, are highlighted for emphasis. The four sections of the chart illustrate: (a) development of an adequate theory and analytical techniques for pre-fabricating and testing of heat pipe devices; (c) adapting heat pipe principles and designs to specific applications and markets; and (d) devising

REFERENCEABILITY OF THE ORIGINAL PAGE IS POOR



#### A. Effective Invention - Not Put to Use

For centuries, heat has been the commodity most widely produced, transferred, controlled, and used in all walks of life. What more could there be to learn about heat transfer? Yet not once, but twice since 1940, the principle of the heat pipe has been discovered. Although the effectiveness of vapor heat transfer was well known, the vacuum-vapor heating systems introduced about 1910, did not anticipate the heat pipe; vapor heating systems always require that the boiler be located below the radiators, and depend on some outside force--pumps or gravity--to return the condensate.

The true capillary heat pipe was first developed in the 1940's for use in household refrigerators. R. S. Gaugler, in the General Motors research laboratories, sought a simple and reliable means of coupling thermally the main food compartment and the frozen food storage chest located below the main chamber. His patent describes tubes containing fine fiber glass wicks and a volatile fluid such as ammonia, capable of transferring heat *downwardly* from the food compartment to the primary evaporator near the freezer. However, this development was never carried to the production stage. The patents expired, and the work done by Gaugler lay dormant and largely unknown for nearly 20 years.

Gaugler correctly observed the effect of an inert, noncondensable gas introduced in the heat pipe, describing the use of this "buffer" gas to control thermal conductance, thus preventing over-cooling of the upper food compartment. Such control and modulation of heat pipes was destined to become one of the most important areas of development in the late 1960's.

#### B. Rediscovery

The modern form of the heat pipe was independently reinvented in 1963 to meet requirements of the nuclear and space power program. At the Los Alamos Scientific Laboratory of the University of California, Dr. George Grover and others were engaged in developing high temperature energy conversion technology using radioisotope heat sources. Thermionic and thermoelectric nuclear power systems required a heat transfer device having extremely high effective thermal conductance. The device developed to meet this need was what Dr. Grover called the "heat pipe."

The first description of the heat pipe in the open literature appeared in June 1964. Grover and Cotter disclosed the principles of the capillary heat pipe, and its exceptional thermal performance. It is significant that this key paper was entitled, "Structures of Very High Thermal Conductivity." During the first few years, the attention devoted to heat pipes focused almost exclusively on this one property--an effective thermal

conductance more than 1,000 times better than any known metal. Only after more experience had been gained with heat pipes did it become apparent that additional characteristics of these devices were at least as important, and often more useful, than the amount of heat transmitted.

### C. Commercial Production

The thermal conductivity of the Grover heat pipe was so extraordinary that within a few months, the first commercial venture was launched. RCA became the pioneer heat pipe company, starting work in December 1963. The Direct Energy Conversion Department, headed by G. Yale Eastman, developed a broad marketing approach, specializing in thermionic power generators and electronic device cooling systems. RCA worked with NASA, the AEC, and industrial organizations for more than 7 years. During this time, they built and tested several thousand heat pipes, in more than 60 different design configurations. RCA's heat pipes were of high quality, and were well adapted for specific uses, but the market was slow to develop because the idea was new. During the recession of 1970, the company ceased external marketing, and today manufacture and use heat pipes only in special RCA electronic devices.

Elsewhere in the space program, other workers had also been developing capillary heat transfer systems. At Jet Propulsion Laboratory, Laub and McGinness had investigated a Freon evaporator boiler to supply gas bearings on unmanned spacecraft. Laub used the capillary pumping principle to return the condensate back to the evaporator section under weightless conditions. Detailed analysis of this two-phase flow, and the first screen capillary pump, followed 1 year later by Thostesen at JPL. For the passive control of space suit temperature and humidity, Shlosinger developed wick-fed water evaporators as heat sinks. At NASA's Lewis Research Center, Haller and his associates developed the fin-tube radiator concept using capillary wicks to maintain fluid flow under zero-G conditions. Spacecraft thermal control systems, and devices for cooling on-board electronic components, were developed by Katzoff at Langley Research Center. Important contributions were made to the theory of heat pipe operation, and the design and performance of wick structures were significantly advanced. The first artery wicks were developed at Langley. These pioneering studies of screen arteries and spiral arteries helped make possible many of the high-performance heat pipes that would be developed in later years.

There was sufficient worldwide interest in heat pipes for spacecraft and nuclear applications to prompt a conference bringing together workers from Europe and the United States. The AEC/Sandia Heat Pipe Conference in 1966, focused attention on the versatility and wide range of applications for these new heat transfer devices. In comparing experimental results with the theoretical predictions, experts found that heat pipes did

not always perform as expected. The Sandia Conference pointed out the need for better understanding of heat pipe mechanisms and dynamic theory, as well as the need for compatible materials, better wicks, practical fabrication methods, and information concerning operating lifetimes. In addition to extremely high thermal conductance, operating characteristics such as temperature uniformity and heat-flux transformation began to receive more attention.

#### D. Theory, Analysis and Prediction

An important difference between heat pipe development and many other innovations was the need to develop fundamental theories capable of explaining the operation of this deceptively simple device. Most technical developments represent some significant improvement over a previous technology. There is often a smooth transition from the prior art, allowing incorporation of the innovation in advanced engineering, without requiring the development of new theories. In the case of heat pipe development, the order of the day was: *Back to basics*. Fundamentals of thermodynamics, fluid flow, capillary action, and gas dynamics of two-phase flow were invoked to develop an equilibrium theory of heat pipes. Cotter, Katzoff, Marcus, and Busse in Europe, among others, made important contributions to the theory and functional analysis of heat pipes.

With increasing experience, it became clear that while heat pipes were at first considered a thermal superconductor, their behavior was sufficiently complex that they could not be characterized by any single property such as equivalent thermal conductance. Nor could heat pipe operation be fully explained or predicted from the steady-state equations. What had been considered as a passive thermal device was--inside its shell--a highly dynamic and complex system, with transient behavior and sometimes troublesome start-up dynamics. Evaporation of the working fluid altered surface energy and capillary flow behavior of the fluid. The best wick action was not always obtained with small capillaries. Loosely bonded wicks (essentially artery wicks) showed higher performance than tightly fitted wicks. As heat pipes were pushed to higher levels of heat transport, abrupt changes indicated the existence of different regimes of operation. "Amazingly simple principle," indeed!

#### E. First Uses in Space

The first orbital test demonstrating heat pipe operation under zero-G conditions took place in 1967. The launch vehicle for the ATS-A satellite carried a heat pipe with thermocouples to determine its temperature uniformity and performance under varying heat loads throughout different portions of its earth orbit. This successful demonstration was followed 1 year later by the launching of GEOS-2, using heat pipes designed

by Johns Hopkins. GEOS-2 was the first satellite designed to use heat pipes as an integral part of its overall thermal control system.

#### F. Initial Emphasis on High Thermal Capacity

Until the late 1960's, surprisingly little attention was given to modification of the basic heat pipe. Many of the first uses were for high-temperature applications, involving nuclear reactors, radioisotope power packages for space applications, and thermoionic or thermoelectric power generators. Considerable emphasis was devoted to designing heat pipes having high thermal capacity.

From 1963 through 1968, technical articles on heat pipes reflect this concern for maximum thermal performance, with virtually no attention to different operating modes or special functions. As late as May 1968, when Scientific American featured a cover article on the heat pipe by Eastman, interest focused on the four primary characteristics of heat pipes:

1. Extremely high thermal conductance; many times the transfer capacity of metals.
2. Ability to separate the heat source and heat sink a considerable distance.
3. "Temperature flattening." Maintaining virtually uniform temperature conditions over a large surface area, despite point-to-point variations in the temperatures of the heat source.
4. Heat-flux transformation. Heat can be concentrated or dispersed; either being added over a small area at high flux and removed over a large area at low flux, or vice versa.

These were the characteristics and advantages of heat pipes that largely dictated major applications. Although workers had previously demonstrated that heat pipes could perform many other functions, there seemed to be little need at that time, for heat pipes that could operate as switches, thermal diodes, heat shields, or automatically maintain a constant temperature.

#### G. Space Applications Require New Functions

Space programs played a major role in extending heat pipe technology into new regimes--moderate temperatures, controlled heat pipes, and cryogenic heat pipe devices.

During the period 1967 through 1970, there was increasing interest in heat pipes for lower temperatures (0° to 200° F) suitable for cooling electronic packages, or maintaining environmental control aboard satellites. Among the largest heat pipes ever constructed, were two 50-foot circumferential hoops built to maintain constant temperature conditions in the 40 x 15-foot thermal chamber at Manned Spacecraft Center, Houston. Methods for controlling heat transfer and holding temperatures within a desired narrow range began to assume greater importance.

#### H. Control of Space Suit Temperature

The art of regulating the temperature and thermal transport properties of heat pipes received new stimulus from an unexpected quarter--the need for controlling the temperature in extravehicular space suits.

In 1964, the Manned Spacecraft Center drew up specifications for the Gemini space suit. One of the goals of the Gemini program was to perform the first extravehicular space walks, and this activity would require the removal of metabolic heat--about 1,200 Btu per hour--from the thermal garment. Early tests showed that this was more heat than could be handled by gas-flow cooling; a more effective heat rejection mean was required. When the first articles on heat pipes appeared, engineers working on space suits recognized a new way to transfer heat through the multilayer suits without using any moving parts.

Dr. Arnold Shlosinger, having joined TRW to continue his work with capillary evaporators for cooling space suits, suggested using part of the suit exterior surface as a thermal radiator. For advanced space suits, such as the "hard suits" being investigated by Vykukal at Ames Research Center, this was an attractive concept, since nearly 35 square feet of suit surface was potentially available--if some means of transferring heat through the suit and spreading it uniformly over the radiator surface could be devised.

Soon after development of space suit thermal control devices began, it was learned that heat pipes had more than the necessary heat transfer capability. The problem was excessive variation in the heat sink temperature. When the external radiator faced away from the sun, heat rejection was too rapid; when it faced the sun, little or no heat was rejected. Some method of regulating or controlling the conductance of the heat pipes was required.

Numerous heat pipe control methods were investigated for space suit thermal balance. The key development was a controlled conductance heat pipe; a thermal switching device using vapor flow control. Other innovations stemming from this work included:

- . Flexible heat pipes.
- . Dual chamber heat pipes.
- . Bonded wick structures.
- . Methods for avoiding freeze-up.
- . Techniques for restarting frozen heat pipes.

Because this knowledge had applications outside and beyond the space suit program, these contributions were summarized in a separate report (NASA-CR-1400)--one of the rare instances in which mission-oriented research results were deliberately separated from their original context in order to broaden and to accelerate application.

#### I. Variable Conductance and Constant Temperature Heat Pipes

One unique and valuable property--the ability of heat pipes to automatically maintain constant temperature--was not widely appreciated for several years. As early as 1964, various workers including Hall of RCA, Wyatt and Anand of Johns Hopkins, and Kirkpatrick at TRW experimented with various heat pipe control methods including several variable conductance designs. The variable conductance heat pipe principle was at first called "power flattening" when introduced for use with radioisotope sources that decayed with time. Temperature variations of less than 1 percent were achieved with changes in input power by a factor of 10. Because certain aspects of isotope temperature control were classified, knowledge concerning these modified heat pipe designs was restricted. The concept and terminology of constant temperature heat pipes did not become widespread for several more years.

During the late 1960's, the theory and design of variable conductance heat pipe control methods was carried forward by Marcus, Kirkpatrick, and others at TRW, and by Bienert at Dynatherm, under sponsorship of NASA's Ames Research Center. The variable conductance principle has been extensively developed since 1969, and providing automatic temperature stabilization is now one of the most important uses of heat pipes. Minimizing temperature variation is highly desirable in electronics, chemical processes, electroplating, the coating of films and papers, and numerous other applications.

The conventional heat pipe transports heat with a negligible temperature drop between evaporator and condenser, so that the midsection is nearly isothermal over its entire length. However, the heat pipe does not have any particular operating temperature. Instead, it automatically adjusts its temperature to match the heat-source and heat-sink conditions.

In numerous applications, it is desirable to maintain some selected narrow temperature range along the midsection of the heat pipe, despite variations in source or sink conditions. For these uses, it is necessary to actively or positively control heat pipe conductance so that it holds the desired temperature range--the so-called constant temperature heat pipe. Many different control methods have been investigated, with control by means of noncondensable gas receiving the greatest attention. Major control approaches include:

- . Condenser flooding with excess working fluid
- . Vapor flow modulation
- . Liquid flow control
- . Gas control
  - heater controlled reservoir
  - fluid actuated bellows
- . Thermal diodes (one-way heat pipes)
- . Phase change material thermal accumulator

The first gas controlled variable conductance heat pipe to fly was launched in August 1972, on the Orbiting Astronomical Observatory, (OAO-C). The gas controlled heat pipe maintained the on-board data processing electronics at  $65 \pm 5^\circ \text{F}$  for changes in power dissipation from 15 to 35 watts as shown in Figure 3. Thermal control methods previously used had resulted in temperatures varying from  $0^\circ$  to  $140^\circ \text{F}$ .

#### J. Cryogenic Heat Pipes

The temperature range of interest gradually progressed from  $+3000^\circ \text{F}$  down to the subzero range. Cryogenic heat pipes present special problems. Because liquefied gases are not very good working fluids for heat transfer, the early cryo-pipes studied by the U.S. Air Force were rather low-performance devices, extremely sensitive to gravity fields, and not working effectively with the usual wick structures. More extensive research, starting in 1970, has dramatically improved both the theory and practical arts of cryogenic

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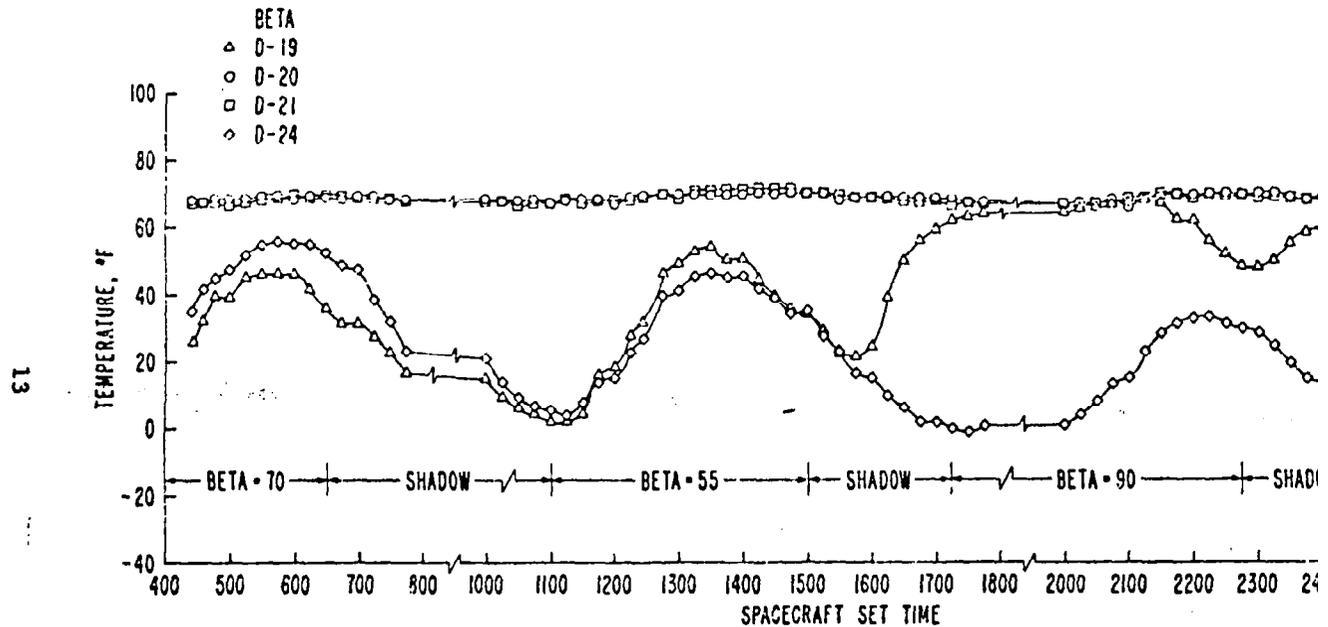


Figure 3

Source: Ames Research Center

heat pipe technology. The axial-grooved wick and the pressure-primed tunnel artery have increased heat flux capacity by a factor of 10. The Integrated Cryogenic Isotope Cooling Engine System (ICICLE) developed for Goddard, uses high-performance cryogenic heat pipes. Today, sensors and electronic components can be efficiently cooled; operation against gravity or in rotating systems is practical; and thermal capacities in excess of 4,000 watt-inches (power times length) are readily attainable. Cryogenic refrigeration systems on earth, as well as in space application, can make use of these principles.

### III. Space Requirements and Contributions

Heat pipe technology has been almost totally developed through government funded research. The initial industrial concept did not lead to use; the urgent requirements of the nuclear and aerospace programs provided the stimulus to advance the state of the art. From 1963 to 1969, virtually all of the key developments were achieved to satisfy the needs of various sponsoring agencies indicated in Table 1. Since 1968, an increasing amount of development, design, and especially adaptation to specific uses, has been conducted by private industry. The number of industrial patents issued for heat pipe applications has increased rapidly since 1969. However, most of the basic knowledge concerning heat pipe theory and operation was generated in response to requirements and opportunities for space applications. Table 2 shows the major space requirements to be satisfied, specific space programs, and typical contributions. Several requirements were intrinsically achieved by the basic operating characteristics of the heat pipe, thus needing only optimization and demonstration of these capabilities.

One particular space contribution not shown in this table needs separate comment--dissemination of this new technology. It was essential to develop, improve, and modify the basic heat pipe to satisfy numerous space needs. The widest possible sharing of knowledge would help accelerate those developments, encourage utilization, improve quality and reliability, and, ultimately reduce costs by making heat pipes relatively standard, familiar components.

To promote awareness and use of heat pipe technology, a variety of special methods have been used to provide effective dissemination of current knowledge:

- . Design handbooks
- . Bibliographies (with continuing updates)
- . Conferences

TABLE 1

MAJOR GOVERNMENT FUNDED HEAT PIPE DEVELOPMENT PROGRAMS

- NASA
  - AMES RESEARCH CENTER
  - GODDARD SPACE FLIGHT CENTER
  - MANNED SPACECRAFT CENTER
  - MARSHALL SPACE FLIGHT CENTER
  - LEWIS RESEARCH CENTER
  - LANGLEY RESEARCH CENTER
  - JET PROPULSION LABORATORY
- AEC
  - LOS ALAMOS SCIENTIFIC LABORATORY
  - LAWRENCE LIVERMORE LABORATORY
- AIR FORCE
- NAVY

TABLE 2

SPACE REQUIREMENTS AND CONTRIBUTIONS

<u>REQUIREMENTS</u>	<u>SPACE PROGRAM CONTRIBUTIONS</u>	<u>ADVANCES</u>
HIGH THERMAL POWER SEPARATION OF HEAT SOURCE HEAT SINK	● SOLAR CONCENTRATORS SNAP THERMIONIC CONVERTERS	LIQUID METAL HEAT PIPES LENGTH UP TO 70 FEET
ZERO-G-OPERATION COUNTER-G-OPERATION	● ORBITAL WORKSHOP COMMUNICATION SATELLITES	MANY WICK DESIGNS, THREAD ARTERY, EHD AUGMENTATION
LIGHTWEIGHT NO EXTERNAL POWER NO MOVING PARTS	● ALL	DESIGN OPTIMIZATION
91 LONG LIFE/RELIABILITY	● ALL	COMPATIBLE MATERIALS LIFE TEST SCALING
HEAT FLUX TRANSFORMATION	● LUNAR SURFACE MAGNETOMETER TWT COOLING	(INTRINSIC PROPERTY OF H.P.)
ISOTHERMALIZE LARGE AREA TEMPERATURE FLATTENING	● GEOS-2 OAO-C	(INTRINSIC PROPERTY OF H.P.)
MAINTAIN CONSTANT TEMPERATURE	● ON-BOARD PROCESSOR AMES H.P. EXPERIMENT	NUMEROUS VARIABLE CONDUCTANCE DESIGNS FEEDBACK CONTROL
SPECIAL OPERATION	● SPACE SUIT RECTIFIERS	THERMAL SWITCH THERMAL DIODE THERMAL ACCUMULATOR EHD PUMPING AXIAL GROOVE WICK PRESSURE PRIMED ARTERY

- . Computer program exchanges
- . Workshops and short courses
- . Evaluation of cost-effective fabrication
- . Standards for specifying heat pipes

Representative of these special information resources is the Heat Pipe Technology bibliography and abstracts prepared by NASA's Technology Applications Center at the University of New Mexico. Several companies now engaged in marketing commercial heat pipe devices indicated that their decision to enter the field was influenced to a major degree by the information obtained through these sources.

#### IV. Significance and Impact

Ten years have passed since the heat pipe principle was rediscovered. What assessments of the significance of these devices can be made at this time?

One measure of activity in the field is reflected in the growth of the technical literature. Figure 4 shows the rapid increase in the number of articles, books and patents covering heat pipe applications. New findings are appearing at a current rate of nearly 200 publications annually. Several thousand engineers and scientists around the world are working to exploit the properties of heat pipe. Approximately 40 U.S. organizations and a score of universities currently maintain active heat pipe research and development programs. The interest is worldwide; more than 30 foreign companies and governmental organizations have acquired the new technology and are vigorously exploiting applications. A listing of present factors in the United States and Europe follows the chronology sections, and indicates the principal fields of specialization.

It should be noted that heat pipe technology has not been fully assimilated into traditional manufacturing industries. Thus far, heat pipes continue to be manufactured and sold by highly specialized firms.

The principal U.S. producers include:

Q-Dot Corporation - Dallas, Texas  
 Isothermics, Inc. - Clifton, New Jersey  
 Heat Pipe Corporation of America - Newark, New Jersey  
 Noren Products - Redwood City, California

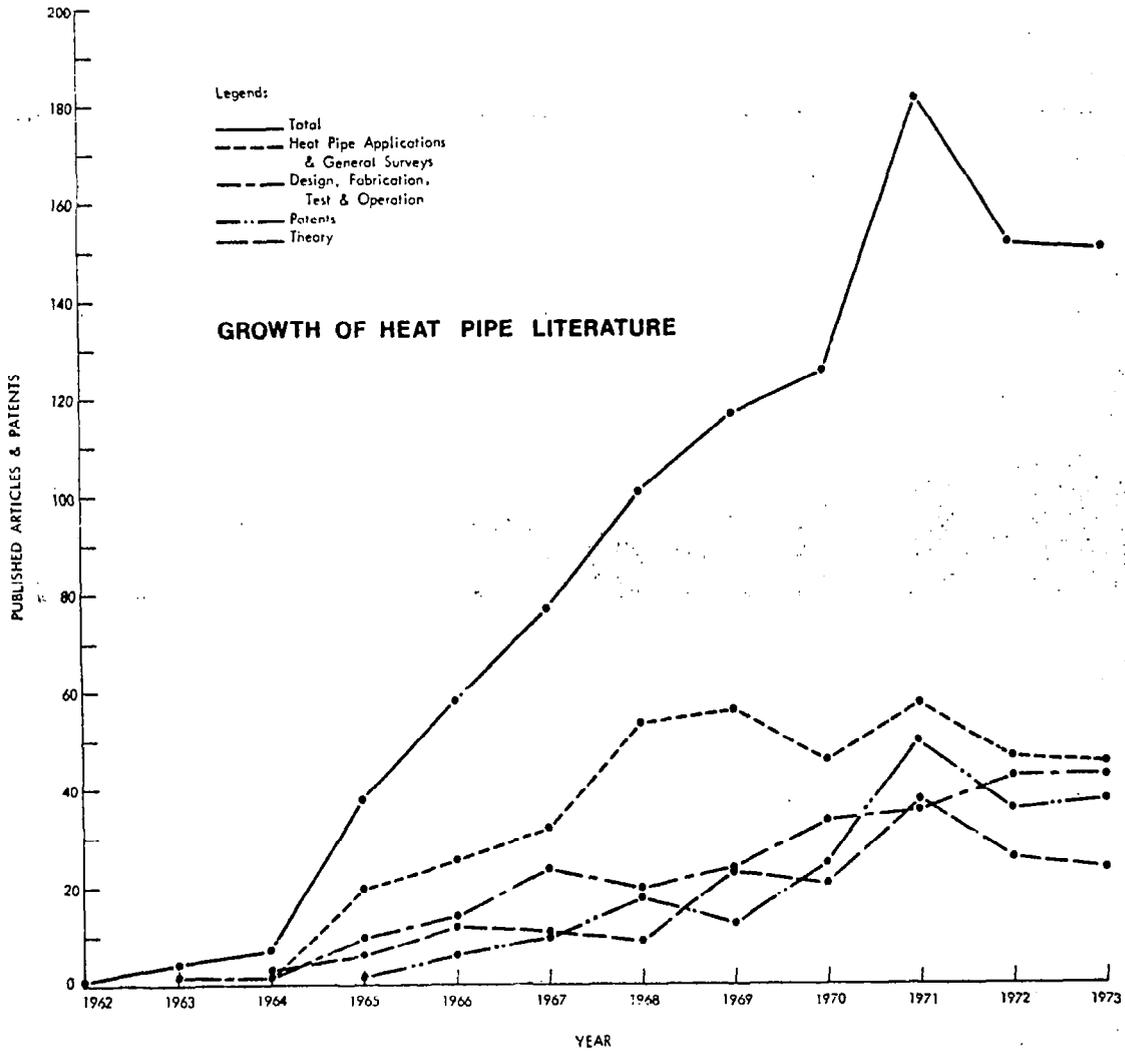


Figure 4

Source: Midwest Research Institute; derived from "Heat Pipe Technology" - Bibliography.

Thermoelectron Corporation - Waltham, Massachusetts  
TRW Systems Group - Redondo Beach, California  
Jermyn Industries - San Francisco, California  
Dynatherm Corporation - Cockeysville, Maryland  
Donald W. Douglas Laboratories - Richland, Washington  
Hughes Electron Dynamics - Torrence, California  
Energy Conversion System, Inc. - Albuquerque, New Mexico  
Grumman Aerospace Corporation - Bethpage, New York

In addition, about a dozen firms offer the special tubing and wick materials used in the fabrication of heat pipe devices.

Only within the past few years have heat pipes started to gain commercial acceptance. The first two commercial ventures found that the market was not yet developed, or that special applications did not match their marketing capabilities. RCA has ceased external marketing both in the U.S. and in Britain. Energy Conversion Systems, Inc. began in 1966 as a spin-off from the mechanical engineering department at the University of New Mexico. This company specialized in industrial applications, primarily electronics cooling. However, their best known product was the "Thermal Magic" cooking pin, a heat pipe that cut the cooking time for large pieces of meat to one-half the usual period. Some 20,000 units were sold, and independent tests have proven the efficiency of the device. However, the household and commercial food preparation market did not prove particularly profitable. The company continues to market stock sizes of heat pipes for use in equipment made by other firms.

Viable commercial markets for heat pipes began to emerge after 1970. The heat pipe has replaced many conventional heat transfer systems, and effective use of heat pipe characteristics often makes otherwise marginal devices highly practical. Numerous different shapes and sizes of heat pipes have been introduced. Some heat pipe devices such as the vapor chamber griddle shown in Figure 5 bear scant resemblance to the more familiar tubular designs. The great number and extreme diversity of present uses makes it helpful to classify applications according to the primary heat transfer function; or according to the field of use. Table 3 summarizes some of the growing list of heat pipe applications.

#### 4. New Requirements Create Markets

The important role of new and nontraditional applications deserves

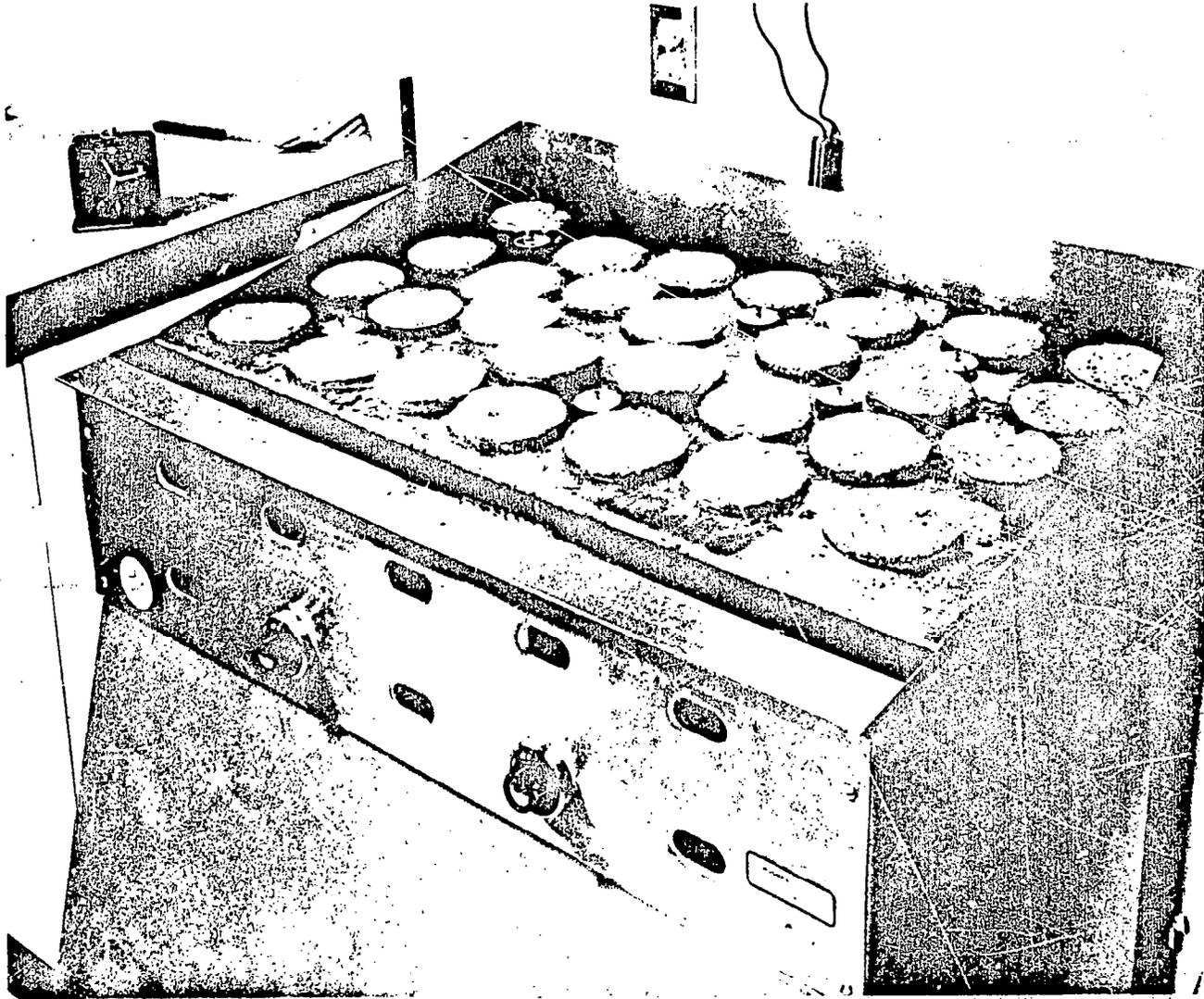


Figure 5 - Vapor Chamber Griddle Provides Uniform Surface Temperature and Quick Warm-up

Source: Hughes Electron Dynamics Division

TABLE 3

HEAT PIPE APPLICATIONS

By Major Heat Transfer Function

Heating

Thermal recovery units, winter heating  
Space heating from flue-gas, fireplaces  
Industrial process heat recycle  
Aircraft wing deicing  
Warming carburetors, air intakes  
Stirling engines, Brayton cycle engines  
Deicing highway bridges, intersections  
Solar energy collectors  
Geothermal energy recovery  
Thermoelectric hot shoes  
Thermionic emitters  
Coal gasification  
Chemical reaction vessels  
Heat recuperators, air preheaters  
Mobile home furnace/hot water heater combination units

Cooling

Air conditioning precoolers  
Electric motors, transformers  
Switchgear, circuit breakers, starters  
Electric bus bars  
Storage batteries, fuel cells  
High power electron tubes, TWT's  
Power rectifiers, SCR's, transcaent rectifiers  
Electronic rack cooling, high density packaging  
Turbine shafts and blades  
Lathe cutting tools, drills  
Foundry and die casting molds  
Injection molding machines and dies  
Disc brakes, auto and aircraft  
Motorcycle crankcase cooling  
Fission product storage vaults  
Space suit temperature control

TABLE 3 (Concluded)

Temperature Control, Isothermalization, Other

Crystal oscillator ovens  
Inertial guidance gyros  
Electroplating baths  
Temperature regulation for data processing electronics  
Coating rolls and doctor blades  
Isothermal furnaces, semiconductor diffusion  
Black-body radiation cavities  
Spacecraft structures, isothermalization  
Isothermal mounting plates for electronics  
Telescopes, optical equipment  
Surgical cryoprobe, dermatology, etc.  
Infra-red detector cryogenic cooling  
Laser mirror cooling, laser tuning  
Directional casting, heat treating

practical benefits provided by heat pipe technology. Selected uses of heat pipes to satisfy requirements that were largely unforeseen in 1963 will be described briefly.

#### B. Permafrost Stabilization

The largest single market currently for heat pipes is for environmental protection along the trans-Alaska pipeline. The warm pipeline will be supported above the arctic tundra by thermal piles with internal heat pipes extending many feet into the permafrost layer. Operating as a thermal diode, the heat pipes will help freeze and subcool the soil to full depth in winter when air temperatures are low. In the summer, the heat pipe thermal piles will be inactive and the permafrost will thaw only near the surface. By maintaining a solid mass of permafrost around each supporting pile, heaving and shifting of the soil will be reduced and pipeline settling can be avoided. Without this thermal protection, uncontrolled freezing and thawing of the soil could stress the crude oil line to the point of rupture. Protecting the delicate tundra environmentally by keeping the permafrost frozen was a significant consideration in assessing the environmental impact of the project.

Several aerospace contractors are involved in the design and life testing of heat pipes for Alyeska. Nearly 110,000 heat pipes using ammonia fluid and steel tubes, up to 50 feet in length, will be required, with a total cost of approximately \$40 million. Figure 6 shows heat pipes being tested to determine performance and reliability. Among the most challenging aspects of the design of these heat pipes was the scaling of conditions for accelerated life test and reliability prediction. The pipeline is designed to have an operating life of 30 years. Accelerated life tests at high temperatures were accomplished in approximately 4 months to demonstrate that heat pipes will function properly for 30 years.

#### C. Energy and Fuel Conservation

Heat pipes are now helping homeowners to stretch scarce fuel oil supplies. In many oil-fired furnaces, 25 to 30 percent of available heat is lost in hot flue gas up the stack. The Air-O-Space heater introduced by Isothermics, Inc., uses heat pipes to extract flue gas waste heat, and can normally recover from 7,000 to 10,000 Btu per hour. Figure 7 shows a typical installation that can increase heating system efficiency approximately 10 percent, thus reducing domestic heating oil consumption.

Industry is rapidly adopting heat pipe thermal recovery units that can dramatically reduce energy consumption and operating costs. The first industrial units to recycle waste heat were introduced in 1971 by Q-Dot Corporation, founded by George Grover, discoverer of the modern heat

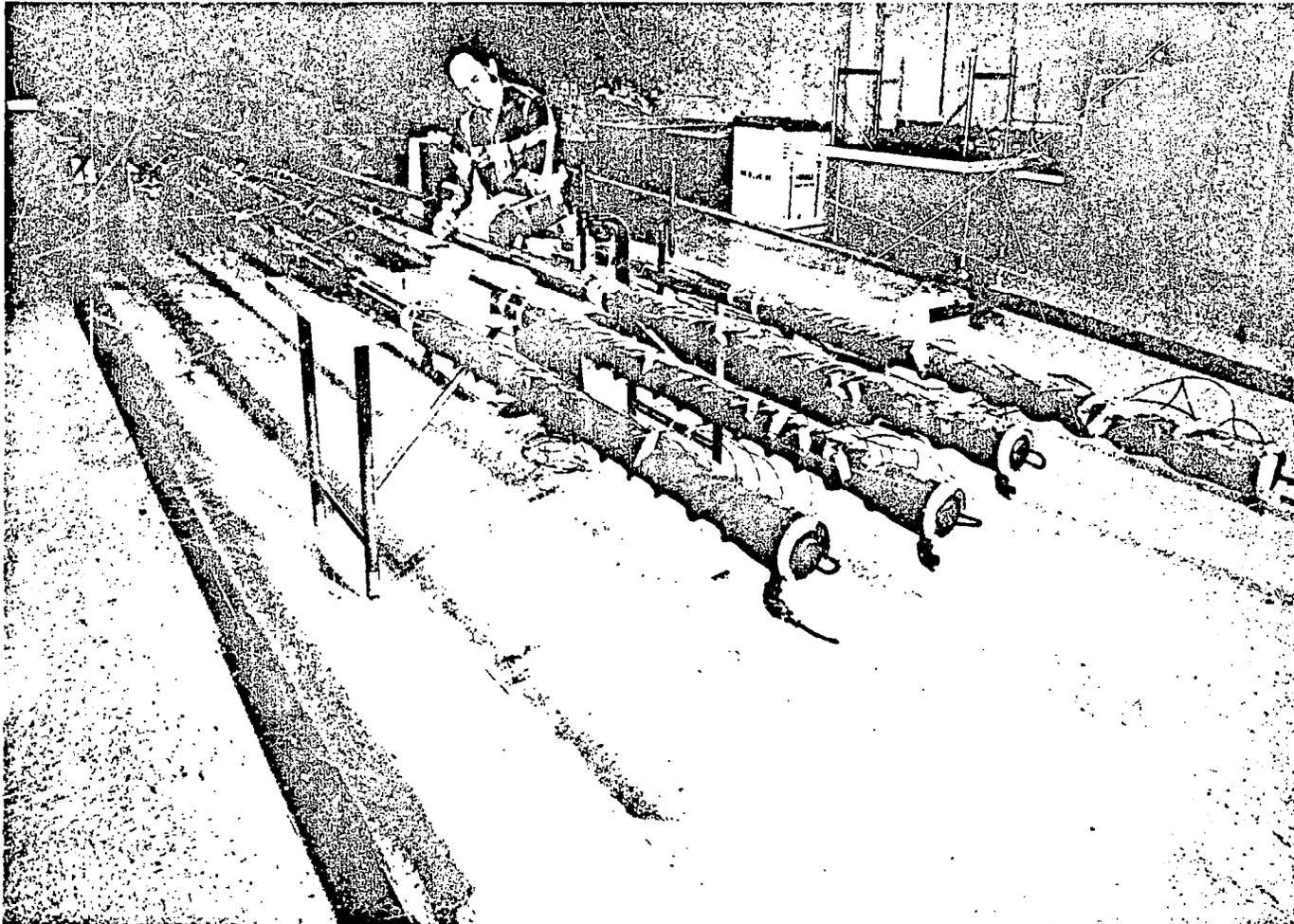
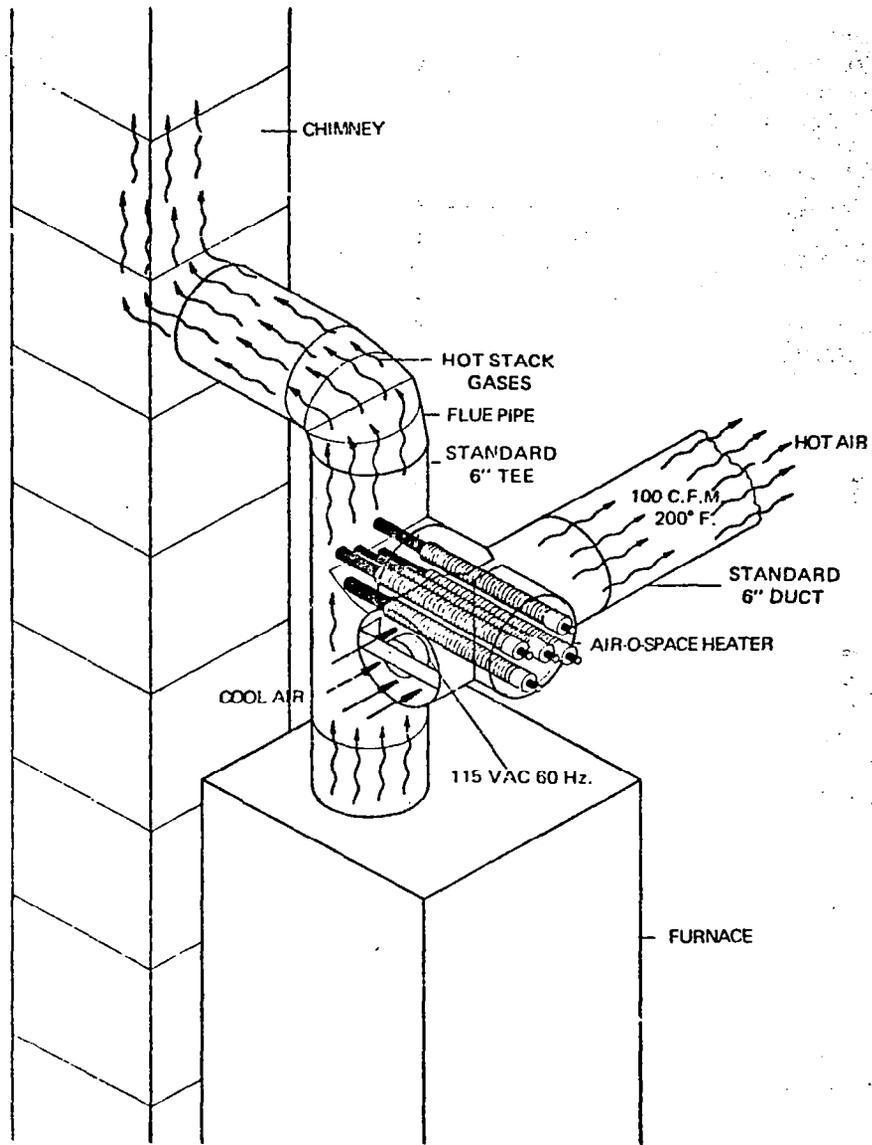


Figure 6 - Testing Heat Pipes for Trans-Alaska Pipeline.  
Each pipe removes 400 watts of heat.

Source: Hughes Electron Dynamics Division



pipe. Figure 8 shows how a thermal recovery unit captures 60 to 80 percent of waste heat from a kiln dryer and returns the heat directly back to the processing kiln.

Energy conservation through heat recovery is becoming essential for industries that need to expand production and are not able to obtain additional supplies of natural gas or other fuels. In addition, the savings from process heat recycling can often pay for the heat pipe recovery system in the first operating year. The widest use of process heat recovery units to date has been in foundries, rubber vulcanizing, paint drying ovens, coffee roasting and spray drying of detergents. In many other industrial plants, waste heat is recovered and used to provide comfort heating for the factory.

Commercial and institutional buildings are obtaining substantial energy and equipment cost savings through the use of heat pipe recovery units in air conditioning, heating and ventilating systems. The heat pipe exchangers work both winter and summer. In winter, heat is transferred from warm building exhaust air to preheat cold incoming fresh air. In summer, the incoming hot air is precooled ahead of the main air conditioner. The heat transfer can be controlled by tilting the thermal recovery unit a few inches, permitting gravity to aid or retard fluid flow in the axial capillary grooves that serve as the wick. Separation of the two air streams by a sealed partition insures that no contamination of the fresh air supply will occur, an important consideration in hospitals and schools. The recovery of waste heat makes it practical to use 25 to 30 percent smaller air conditioning systems, and to reduce heating costs significantly.

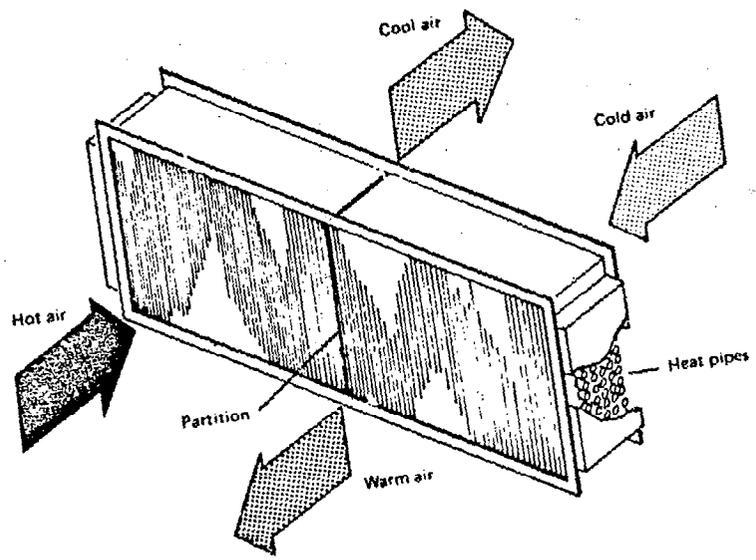
#### D. Cryogenic Surgery

Recent advances in cryogenic heat pipes have made possible a simple cryosurgery instrument. This open-loop heat pipe cooled by liquid nitrogen is a small, hand held, self-contained surgical probe developed by Hughes Electron Dynamics Division, and shown in Figure 9. It brings extreme cold directly to the surgical area at the tip of the instrument. Equally important, the simplicity and modest cost of the unit is bringing cryosurgery into doctors' offices and outpatient clinics rather than requiring elaborate operating room equipment. The "Kryostik" is being marketed for Hughes by the Ritter Company, a medical equipment manufacturer and supplier.

#### E. Isothermal Furnaces

The isothermal or uniform temperature property of heat pipes has been used in precision furnaces for treating integrated circuits, and jet engine turbine blades. An annular heat pipe can conduct externally applied

### THERMAL RECOVERY UNIT



### INDUSTRIAL HEAT RECOVERY

Unit transferring waste heat from a process exhaust directly back into the process.

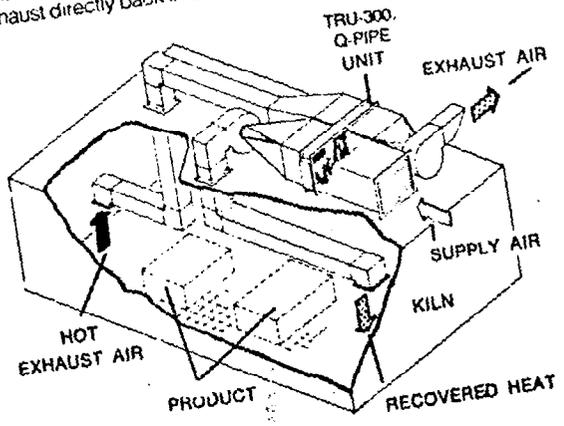


Figure 8

REPRODUCIBILITY OF THE  
SOURCE IS PROOF

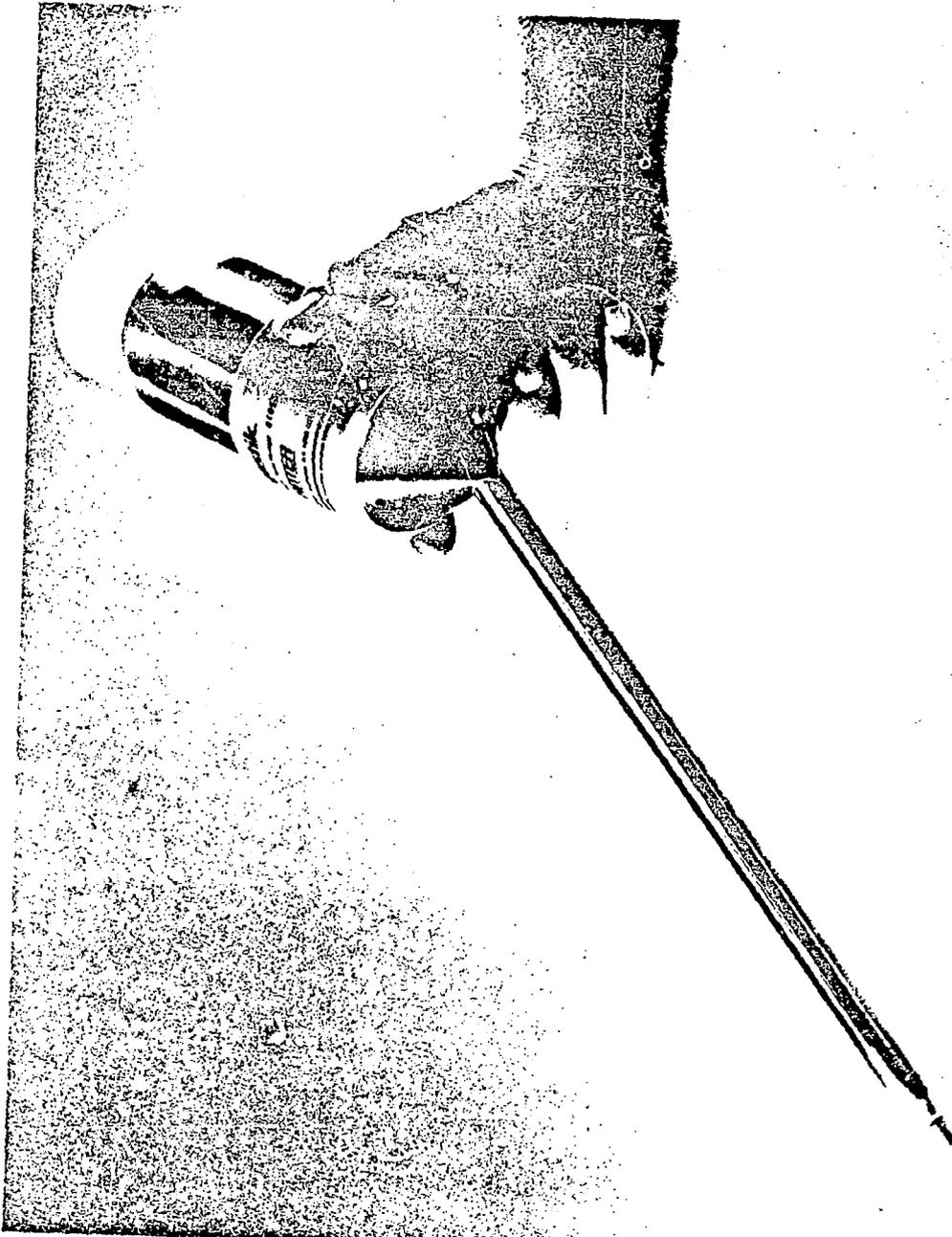


Figure 9 - Open-Loop Surgical Cryoprobe

Source: Hughes Electron Dynamics Division

heat--even nonuniform heating--to the inner surface, so that the temperature of the inner wall is held constant over its entire surface. For scientific purposes, isothermal furnaces are used as "black-body" radiation cavities for calibrating radiation measuring devices and measuring thermal radiation properties of materials.

One of the greatest needs for a truly isothermal furnace is in the diffusion of semiconductor materials used for transistor and integrated circuits. For complex circuit chips, it is essential that all of the semiconductor wafers being processed get exactly the same heat treatment, requiring furnaces having extreme temperature uniformity. The heat pipe principle assures uniform furnace temperatures with greatly simplified controls. An important bonus lies in the ability of the heat pipe furnace to provide uniform temperature while operating in a vertical mode. Isothermal operation of vertical furnaces is difficult, if not impossible, to achieve using normal furnace construction.

#### F. Noise Abatement

New industrial safety and noise abatement codes under the Occupational Safety and Health Administration (OSHA) often require building an acoustic enclosure around noisy machines such as grinders. Without some means of cooling the machine and its motors, overheating can easily occur. Heat pipe exchangers, which penetrate into the sealed enclosure, are ideally suited for such cooling applications because they are small, efficient, automatic in operation, and need no external connections or power.

#### G. Future Markets and Growth

No complete estimates are available to measure the present size and rate of growth in commercial heat pipe devices. All manufacturers reported substantial recent increases in production. Several firms expressed amazement at the number and variety of new uses devised by their customers. With many of the large volume applications stemming from relatively new needs--such as energy conservation--it is difficult to predict the extent of growth even over the next few years.

By combining estimates furnished by established heat pipe makers in Europe and the U.S., some consensus was obtained regarding present market size and anticipated growth over the next few years. These estimates are summarized in Table 4. British production is currently small but is expected to exceed \$1.2 million by 1976. Western Europe represents a somewhat more developed market. In the United States, the demand for heat pipe devices is expected to double or triple by 1976. The heat pipes that will

be used for the Alaska pipeline, will mean an additional \$15 to \$20 million per year during 1975 and 1976. A continuing market for soil stabilization and foundations in the arctic regions is foreseen. Virtually all of the commercial markets have emerged since 1970, so that it is hardly possible to estimate the ultimate significance and impact of this burgeoning new technology.

TABLE 4

ESTIMATED SALES OF HEAT PIPE DEVICES

	<u>1973</u>	<u>1976</u>
Great Britain	\$ 36,000	\$1.2 million
Continental Europe	\$135,000	\$2.3 million
United States	\$8 to \$10 million	\$18 to \$25 million
Alaska	-----	\$20 million

## CHRONOLOGY

### DEVELOPMENT OF HEAT PIPES

- 1899: James A. Trane introduced the vapor heating system which gained acceptance by 1920. Vapor heat transfer provided high thermal capacity and fast response. Typically required vacuum pump, air eliminator, steam traps, condensate return lines, and the boiler was below the radiators for gravity flow return.
- 1945-
- 1948: R. S. Gaugler (General Motors), "Capillary Heat Transfer Device for Refrigerating Apparatus." Describes use of fiber glass strands enclosed in braided fiber glass sleeve as an improved, flexible wick that permits bending metal heat pipes. Density of wick packing varied from low at bottom to high density at top of tube. Glass wick and anhydrous ammonia were the preferred combination, although water or alcohols may also be used. Fibrous wicks claimed superior to the previously used sintered iron powder, which was brittle and difficult to fabricate. Note: Mentions the use of inert gas such as nitrogen introduced into pipe to block off the header and prevent cooling the upper food chamber more than desired. U. S. Patent No. 2,448,261.
- 1950: Eckert and Jackson (NACA), "Analytical Investigation of Flow and Heat Transfer in Coolant Passages of Free Convection Liquid Cooler Turbines." Turbine blades cooled by internal evaporation and condensation. NACA-RM-E-50-D-25 (July 1950).
- 1961: J. H. Laub and McGinness, (Jet Propulsion Lab), recirculation of fluid by thermal evaporation and capillary pumping action. Freon fluid vaporized to supply spacecraft gas bearing, using capillary return from condenser to evaporator. JPL-TR-32-196 (December 8, 1961).
- 1962: L. Trefethen (Tufts University/General Electric), "On Surface Tension Pumping of Liquids, As a Possible Role of the Candlewick in Space Exploration." Speculation proposing the use of evaporation-condensation and capillary pumping concept in the space program. Author commented: "How well this idea would perform in space is apparently not known." (February 1962).

- 1962-
- 1963: Thostesen (JPL). Screen capillary pump in forced convection heat transfer device for spacecraft. Theoretical analysis of the Laub-McGinness wick pump for mass flow rate. Heating affected meniscus in evaporator zone. Stainless steel 150 mesh screen found superior for fluid return from condenser to evaporator. Space Program Summary No. 37-17, p. 145-147; No. 37-20, p. 38, (August 1962 to April 1963).
- 1963-
- 1964: G. M. Grover and T. P. Cotter (LASL), "Structures of Very High Thermal Conductance." Key paper describing heat pipe. J. Appl. Physics, 35, 1990-91 (June 1964).
  - 1963: T. Wyatt (Johns Hopkins/Applied Physics Lab), "Satellite Temperature Stabilization System." Early development of spacecraft heat pipes for temperature stabilization. U.S. Patent No. 3,152,774 (October 13, 1964), application filed June 11, 1963.
- 1963-
- 1965: Shlosinger and Woo, et al., (Northrop). Passive control of humidity in space suits using capillary wick-fed water evaporator. Refrasil wick materials superior to glass fiber. Capillary pumping in zero-G simulated. Target 700 Btu per hour. NAS-2-2102; NASA CR-69098 (September 1965).
- 1963-
- 1964: C. P. Costello. Capillary wicking limits, watability, and burnout limits for a wick boiler. A. I. Ch. E. Journal 10, 393-8 (1964).
  - 1964: H. C. Haller (Lewis Research Center). Analytical study of flat double-wall condenser radiator, compared to a fin-tube radiator. NASA-TN-D-2558 (December 1964).
  - 1964: Manned Spacecraft Center Gemini space suit RFP. Thermal target was rejection of 1,200 Btu per hour. (More than could be removed by gas cooling.)
  - 1964: Campana and Holland (Gulf-General Atomics). Description of heat pipes operating as radiating fins. The six functions of a heat pipe are examined to identify the factors that influence heat pipe design and which determine their minimum size and weight. GA-5676 (September 17, 1964).

- 1964: Wm. Hall (RCA), "Constant Temperature Output Heat Pipe." Patent covering the "power flattening" heat pipe designed to control heat flux from isotope sources to electric power converters. Heat pipe is provided with a noncondensable gas reservoir at the condenser end to prevent large changes in operating temperature as the isotope decays. U.S. Patent No. 3,613,773 (October 19, 1971), application filed December 7, 1964.
- 1964-  
1965: E. L. Long (Anchorage, Alaska), "Mean for Maintaining Perma-Frost Foundations." U.S. Patent No. 3,217,971 covers use of heat pipe device for maintaining a permafrost layer of earth properly frozen.
- 1964-  
1965: Bohdansky, Busse, Grover (Euratom). Heat pipe cooling of nuclear reactors designed for direct thermoelectric power generation. Canadian Patent No. 765,919, filed December 14, 1964.
- 1965: Deverall and Kemme (LASL), "Satellite Heat Pipe." Development and testing of pipes to reduce temperature cycling of electronic components in orbit by transferring heat from an external radioisotope heater.
- 1965: T. Wyatt (Johns Hopkins/Applied Physics Lab), "A Controllable Heat Pipe Experiment for the 5E-4 Satellite." Observation of unwanted hydrogen in an early heat pipe trial led to pioneering study of gas controllable heat pipes in which the amount of heat liberated is proportional to the amount of noncondensable gas present. APL-SDO-1134 (March 9, 1965).
- 1965: B. D. Marcus (TRW), "On the Operation of Heat Pipes." Description and analysis of processes. Relationship of contact angles and thermal conductivity.
- 1965: T. P. Cotter (LASL), "Theory of Heat Pipes." Description of heat pipes and quantitative theory for design and predicting performance of heat pipes is given. LA-3246-MS (March 26, 1965).
- 1965: Langston, et al., (Pratt & Whitney). Vapor chamber fin for space radiators. NAS3-7622 (May 28, 1965-January 1966), NASA-CR-54922.
- 1965: M. Kirkpatrick (TRW). After learning about RCA heat pipes, TRW initiated company funded R&D on isothermal devices and control. Numerous patents, 1969 to 1972. Basis of commercial license package.

- 1965: Haller, et al., (Lewis Research Center). Flat, direct condensing fin-tube radiator for high temperature space power generating systems. NASA-TN-D-2836 (May 1965), NASA-TN-D-3103 (November 1965).

1965-

- 1967: S. Katzoff (NASA LRC), "Heat Pipes and Vapor Chambers for Thermal Control of Spacecraft." Early analytical and experimental effort to develop passive thermal control for spacecraft. Basic work on wicks and arteries, theory and modeling, testing and applications. Sandia Conference, 1966. AIAA Thermophysics Specialist Conference Paper 67-310 (1967).

- 1966: Shlosinger (TRW). Development of heat pipes for thermal control of space suits. Several innovations:
  - flexible heat pipes
  - thermal switch
  - fabrication methods
  - vapor flow control
  - avoidance of freeze-up
  - startup dynamicsNASA-CR-73168 (September 1967); NASA-CR-73270 (September 1968); NASA CR-73271 (September 1968); NASA-CR-1400 (September 1968).

1966: Sandia Corporation/AEC. Heat pipe conference, June 1, 1966, Albuquerque. Important conference brought together key workers throughout the world. AEC Report: SC-M-66-623 (1967).

- 1966: Anand (Johns Hopkins/Applied Physics Lab), "On the Performance of a Heat Pipe." Correlation of theory and test performance data showing differences in the engineering performance of heat pipes in some areas. J. Spacecraft and Rockets, 3, 763-65 (May 1966).

1966: W. L. Haskin (U.S. Air Force). Built and tested the first cryogenic heat pipe. (March 1966).

- 1966: D. W. Grauman (AiResearch). Wick boiler modules as heat sinks to determine performance of fins. NAS8-11291; NASA-CR-89618, 82794.

1966-

- 1970: Ferrell, Cosgrove, et al., (North Carolina State University). A study of the operating characteristics of the heat pipe:
  - Analytical model for predicting limits of operation
  - Capillarity in porous media
  - Vaporization from flooded wick
  - Heat transfer in evaporator zone

- 1966: G. M. Grover, "Evaporation-Condensation Heat Transfer Device." U.S. Patent No. 3,229,759 (January 18, 1966), assigned to AEC. Application filed December 2, 1963.
- 1966: Energy Conversion Systems, Inc. First independent heat pipe concern founded as a spin off from work in the mechanical engineering department at the University of New Mexico. Produced heat pipes for electronics. Introduced the first consumer heat pipe device called "Thermal Magic" cooking pin, designed for roasting meats.
- 1966-
- 1967: P. Brosens (Thermo-Electron/J.P.L.), "Heat Pipe Thermionic Converter." JPL-0951465 (October 1966-December 1967). NASA-CR-83920, NASA-CR-93664.
  - 1967: Feldman and Whiting (Sandia), "The Heat Pipe." A review of heat pipe efforts and progress throughout the U.S. SC-TM-66-2632 (March 1967).
  - 1967: S. Frank (Martin-Marietta), "Heat Pipe Design Manual." First compilation of materials properties and parameters in a form directly useful to the heat pipe designers. Emphasis was largely on the properties of working fluids. MND-3288 (1967).
  - 1967: Kunz, Langston, et al., (Pratt and Whitney), "Vapor Chamber Fin Studies." Wicking materials studied in detail to develop more realistic capillary pumping characteristics. NASA-CR-812 (1967).
  - 1967: Deverall and Salmi (LASL). First heat pipe in orbital test, April 5, 1967. Piggy-back experimental stainless steel and water heat pipe on NASA ATS-E launch vehicle. Demonstrated that zero-G does not affect performance of heat pipe. J. Spacecraft, 4, 1556 (1967).
- 1967-
- 1968: K. T. Feldman and G. H. Whiting, "The Heat Pipe" and "Applications of the Heat Pipe." Two articles designed to acquaint mechanical engineers outside the aerospace fields with the potential and progress in heat pipe developments. Mechanical Engineering, 89, 30-33 (February 1967); 90, 48-53 (November 1968).
- 1968: G. Y. Eastman (RCA), "The Heat Pipe." Cover story for Scientific American drew attention of scientists and engineers throughout the world to the properties and major advantages of heat pipes. Scientific American, 218, 38-46 (May 1968).

- 1968: (Johns Hopkins/Applied Physics Lab), "GEOS-2 Heat Pipe System." The GEOS-2 spacecraft was the first satellite to use a heat pipe as an integral part of its thermal design. NASA-CR-94585 (April 1968).
- 1968: Thermo Electron Corporation/JPL. "Solar Thermionic Generator." A sodium vapor heat pipe incorporated into a solar collector. JPL-951263, NASA-CR-95980.
- 1968: Noren Products Company established to market electronic cooling devices for high density electronics.
- 1968: Conway (General Electric), and Wilmarth (NASA-ERC). Cooling of high power electron tubes in a space vehicle. IEEE, 9th Conference on Tube Techniques, p. 182-190 (1968).
- 1968-  
1974: K. T. Feldman (University of New Mexico). Workshop on Heat Pipe Design and Analysis (April 19-20, 1968). The first in a continuing series of short courses and workshops to provide theory, design, analysis and applications technology to persons wishing to acquire up-to-date heat pipe technology.
- 1968: Phillips, et al., (Donald Douglas Labs), "Low Temperature Heat Pipes Research." Special development of moderate temperature (0° to 200° F) heat pipes to cool spacecraft components. Wick configurations and arteries for water-based heat pipes. DAC-60752P (July 1968).
- 1969: Dynatherm Corporation established by an active heat pipe group at Martin, after Teledyne acquired Martin Nuclear Corporation.
- 1969: A. Basiulis (Hughes). Heat pipes for cooling TWT and other high power electron tubes. ASME Paper 69-HT-25 (1969).
- 1970: Q-Dot Corporation formed by Dr. George Grover, the inventor of modern heat pipes, and H. Barkmann. Specialize in exchangers for energy conservation in buildings and for industrial process heat recovery.
- 1970: Bienert & Brennan (Dynatherm). Feedback controlled variable conductance heat pipe. NASA-CR-73475.
- 1970-  
■ 1974: B. Swerdling, et al., (Gruman Aerospace Corporation). Freon/aluminum pipe using capillary axial grooves for OAO-B Satellite. Thermal diodes designed for ATS-F to be launched in 1974.

- 1970: B. D. Marcus, et al., (TRW). Fifty-foot circumferential heat pipes (one water, one ammonia) for NASA/MSFC chamber thermal vacuum test facility. NASA-CR-114783 (December 1970).
  
- 1971: R. Pessolano (Isothermics, Inc.). Began manufacture and marketing of heat pipes following workshop course at University of New Mexico. Specialize in HVAC exchangers ("Air-O-Space Heater"), industrial devices, water heaters.
  
- 1971: A. Basiulis (Hughes), "Cryogenic Heat Transfer Device." The open-loop "Kryostik" surgical probe. U.S. Patent No. 3,736,936 (June 6, 1971).
  
- 1969-
- 1975: Donald W. Douglas Laboratory. Ammonia heat pipe for ATS-E (1969). Similar system for DAC/OSO (1970). Shuttle leading edge cooling. "Cryo-Anchor" heat pipe developed for permafrost stabilization (1972).
  
- 1972: Hughes Aircraft/Ritter Company. Open-loop cryogenic heat pipe developed for low cost surgical instrument called "Kryostik." Being marketed to medical field by Ritter Company.
  
- 1972-
- 1973: B. D. Marcus (TRW), "Theory and Design of Variable Conductance Heat Pipes." Comprehensive review and analysis of all technical aspects of controlled heat pipes. Design procedures and GASPIPE computer program. High-performance ambient heat pipes. NASA-CR-2018, NASA CR-114530.
  
- 1972-
- 1973: Dynatherm/MSFC, "Heat Pipe Design Handbook," Volumes I and II. Design procedures, data and computer codes for analysis. NAS-9-11927.
  
- 1973-
- 1976: Alaskan Pipeline Heat Pipe Development Program. Permafrost stabilization heat pipes for heated trans-Alaska pipeline; 110,000 pipes required, having working life of 30 years. Cost estimate, \$35 to 40 million.

HEAT PIPE SPECIALISTS--PRODUCERS AND USFRS

A. Suppliers of Materials

Metal Foams

Astro Met Associates, Inc.  
95 Barron Drive  
Cincinnati, Ohio 45215

General Electric Company  
Metallurgical Products Department  
Box 237, General Post Office  
Detroit, Michigan 48238

Gould, Inc.  
Gould Laboratories  
540 East 105th Street  
Cleveland, Ohio 44108

Union Carbide Corporation  
12900 Snow Road  
Parma, Ohio

Metal Felts

Astro Met Associates, Inc.  
95 Barron Drive  
Cincinnati, Ohio 45215

Brunswick Corporation\*  
Technical Division  
1 Brunswick Place  
Skokie, Illinois  
\*Formerly Huyck Metals Company

Screen

Cambridge Wire Cloth  
P. O. Box 399  
Cambridge, Maryland 21613

Michigan Wire Cloth Company, Inc.  
2100 Howard Street  
Detroit, Michigan 48216

Screen (concluded)

Newark Wire Cloth Company  
351 Vernon Avenue  
Newark, New Jersey 07104

Tobler, Ernst and Traver, Inc.  
420 Saw Mill River Road  
Elmsford, New York 10523

Composite Screen

Aircraft Porous Media, Inc.  
32 Sea Cliff Avenue  
Glen Cove, New York 11542

Finned Tubing

Noranda Metal Industries, Inc.  
French Tube Division  
P. O. Box 558  
Newtown, Connecticut 06470

Porous Metals

Union Carbide Corporation  
Stellite Division  
1020 West Park Avenue  
Kokomo, Indiana 46901

B. Fabricators and Vendors

Donald W. Douglas Labs  
Richland, Washington

Dynatherm Corporation  
Cockeysville, Maryland

Grumman Aerospace Corporation  
Bethpage, New York

Hughes Electron Dynamics Division  
Torrence, California

TRW Systems Group  
Redondo Beach, California

Thermoelectron Corporation  
Waltham, Massachusetts

Energy Conversion Systems, Inc.  
Albuquerque, New Mexico

Heat Pipe Corporation of America  
Newark, New Jersey

Isothermics, Inc.  
Clifton, New Jersey

Jermyn Industries  
San Francisco, California

Noren Products  
Redwood City, California

Q-Dot Corporation  
Dallas, Texas

C. Heat Pipe Users

Buy or make heat pipes for their own equipment without selling the finished product (incomplete list).

<u>U.S. Organizations</u>	<u>Product or Application</u>
Los Alamos Scientific Lab (AEC), N.M. Oak Ridge National Lab, Tennessee Argonne National Lab, Illinois	Thermal control of Reactors, Irradiation capsules, theory, and other applications
NASA Research Centers Ames, Lewis, Goddard, Marshall, Langley	Temperature control of electronic systems and other applications
Jet Propulsion Laboratory Pasadena, California	Electronics cooling, and other applications
National Bureau of Standards Boulder, Colorado	Black body cavities, vapor laser cavities
Sandia Labs, Albuquerque, N.M. (AEC Lab)	Electronic cooling
Wright Patterson Air Force Base, Ohio	Electronic cooling, cryogenic heat pipe
U.S. Army, Fort Belvoir, Virginia	Electronic cooling
Lawrence Livermore Lab, California	Experiments, fusion reactor cooling study
Battelle Memorial Institute Columbus, Ohio	Basic studies
U.S. Navy, Office of Naval Research	Research support
Raytheon Company Bedford, Massachusetts	Electronic cooling
AiResearch Manufacturing Company Los Angeles, California	Experiments
Electronic Communications, Inc. St. Petersburg, Florida	Electronic cooling

C. Heat Pipe Users (Continued)

U.S. Organizations

Product or Application

Bendix Corporation  
Navigation and Control  
Teterboro, New Jersey

Electronic cooling

Gulf General Atomics  
San Diego, California

Survey for fin cooling

Martin Marietta Corporation  
Baltimore, Maryland,  
Denver, Colorado

Electronics cooling

Pratt and Whitney Aircraft  
East Hartford, Connecticut

Basic theory and experiments

Aerospace Corporation  
El Segundo, California

Basic experiments

Sanders Association, Inc.  
Nashua, New Hampshire

Electronics cooling

Collins Radio  
Cedar Rapids, Iowa

Experiments

Philco-Ford, Space Division  
Palo Alto, California

Electron tube cooling,  
avionics cooling

Brown Engineering, Inc.  
Huntsville, Alabama

Spacecraft thermal  
control study

Fairchild Hiller Corporation  
Germantown, Maryland  
Farmingdale, New York

Satellite thermal control,  
thermionic converters

Aerojet Liquid Rocket Company  
Sacramento, California

Rocket motor cooling study

Aerojet General, Nucleonics  
San Ramon, California

Liquid metal studies

Teledyne, Inc.  
Timonium, Maryland

Thermoelectric converter  
cooling

C. Heat Pipe Users (Continued)

U.S. Organizations

Perkin-Elmer Corporation  
Danbury, Connecticut

Bell Laboratories  
Naperville, Illinois  
Whippany, New Jersey  
Murray Hill, New Jersey

North American Rockwell Corporation  
Space Division, Downey, California

Northrup Corporate Laboratories  
Hawthorne, California

Sperry Rand, Space Support Division  
Huntsville, Alabama

Battelle-Northwest  
Richland, Washington

Product or Application

Cryogenic heat pipe for  
IR cooling

Electronics cooling

Satellite thermal control

Basic studies,  
electronic cooling

Basic studies

Basic studies

C. Heat Pipe Users (Continued)

Universities

University of New Mexico  
University of California at  
Los Angeles  
North Carolina State University  
Lehigh University  
University of California at Berkeley  
Colorado State University  
Navy Post Graduate School  
John Hopkins University, Applied  
Physics Lab  
Case Western Reserve University  
Kansas State University  
Catholic University  
California Tech  
Massachusetts Institute of Technology  
Brooklin Polytechnic Institute  
University of Illinois  
Texas A&M  
University of Idaho  
George Washington University  
New York University  
Fordham University  
University of Missouri  
Iowa State University  
Purdue University  
Louisiana State University  
Princeton University  
University of Iowa  
Georgia Tech  
Washington University

Product or Application

Research, testing,  
development studies

C. Heat Pipe Users (Continued)

Non-U.S. Organizations

Product or Application

Eratom Lab  
Ispra, Italy

Experiments, liquid metals for  
high temperature, theory, etc.

IKE, University of Stuttgart,  
Germany

Experiments, development for  
applications.

National Society for Construction  
of Aviation Engines  
Paris, France

Gas turbine cooling studies

Technical High School  
Stuttgart, West Germany

Experiments

Royal Aircraft Establishment  
Farnborough, England

Sacellite heat transfer

Jermyn Manufacturing  
Vestry Estate  
Seven Oaks, Kent, England

Electronics cooling devices

Central Electricity Generating Board  
London, England

Experiments

National Research Council  
Mechanical Engineering Division  
Ottawa, Canada

Theoretical study

French Atomic Energy Commission  
Grenoble, France

Experiments

Institute for Nuclear Physics and  
Reactor Technology  
Karlsruhe, West Germany

Experiments

United Kingdom Atomic Energy Authority  
Harwell, England

Experiments

Philips Research Labs  
Eindhoven, Netherlands

Basic studies

University of Wales  
Institute of Science and Technology  
Cardiff, Wales

Domestic heating study

C. Heat Pipe Users (Continued)

Non-U.S. Organizations

Product or Application

Hawker Siddeley Dynamics  
Space Division  
Stevenage, England

Spacecraft thermal control

European Space Research Organizations  
Noordwijk, Netherlands

Spacecraft thermal control

National Center for Space Studies  
(CNES), Cannes, France

Space radiator

International Research & Development  
Company, Ltd.  
New Castle Upon Tyne, England

Satellite thermal control

Reading University  
Reading, England

Nuclear reactor cooling

University of Swansea, Mechanical  
Engineering  
South Wales, England

Rotating heat pipe studies

Institute for Heat and Mass Transfer  
Soviet Academy of Sciences  
Minsk, USSR

Basic studies

Boris Kidric Institute Lab  
Belgrade, Yugoslavia

Basic studies

Moscow Power Engineering Institute  
Moscow, USSR

Basic studies

Tel-Aviv University  
Tel-Aviv, Israel

Basic studies

MAN, Augsburg  
West Germany

Basic studies

Brown, Boveri and Cie, AG  
Central Research Lab  
Heidelberg, West Germany

General studies, thermionics

C. Heat Pipe Users (Concluded)

Non-U.S. Organizations

Technical University  
Applied Physics Department  
Delft, Netherlands

Technical Institute  
Kiev, USSR

National Institute for Research in  
Science  
Chilton, England

National Gas Turbine Establishment  
Pyestock, England

National Engineering Lab  
Applied Heat Transfer Division  
East Kilbride, England

University of Genoa  
Genoa, Italy

Thomson-CSF  
Electron Tube Group  
Essonne, France

Institute for Machine Design  
Thermodynamics Department  
Bechovice, Prague,  
Czechoslovakia

Product or Application

Basic studies of wicks

High temperature heat pipes

Nuclear/physics experiment

Gas turbine cooling studies

Basic studies

Heat pipe plasma oven

Thermionic converters

General studies

D. Heat Pipe Users

Commercial device marketing.

RCA, Lancaster, Pennsylvania  
Camden, New Jersey

(First commercial firm)  
Electronics cooling, and other  
applications  
(No longer active)

General Electric Company  
Schnectady, New York  
Cincinnati, Ohio  
Philadelphia, Pennsylvania  
Valley Forge, Pennsylvania  
Erie, Pennsylvania

Electronic cooling,  
electric motor cooling,  
transformer cooling

Westinghouse  
Pittsburgh, Pennsylvania

Experiments

Dynatherm Corporation  
Cockeysville, Maryland

General use, solar collectors,  
electronics cooling, isothermal  
ovens, and other applications

TRW Systems, Inc.  
Redondo Beach, California

General use, temperature  
control, electronics cooling,  
isothermal oven, and other  
applications

Hughes Aircraft Company  
Electron Dynamics Division  
Torrance, California

General use, electronics  
cooling, TWT cooling,  
crossurgery device, and  
other applications

Grumman Aerospace Corporation  
Bethpage, New York

Aerospace and other  
applications

Donald W. Douglas Labs  
Richland, Washington

General use, permafrost  
stabilization, other  
applications

Thermo Electron Engineering Corp.  
Waltham, Massachusetts

Energy conversion device  
use, general use

Litton Industries  
Electron Tube Division  
San Carlos, California

Electron tube cooling

D. Heat Pipe Users (Concluded)

Energy Conversion Systems, Inc. Albuquerque, New Mexico	General use, cooking pin, electronic cooling
Q-Dot Corporation, Dallas, Texas	Air-to-air heat exchangers
Isothermics Corp., Clifton, New Jersey	General use, heat exchangers, other
Noren Products Redwood City, California	General use, electronics cooling
Dornier Systems, GmbH Friedrichshafen, West Germany	Solar collector, cryogenic, others

E. Technical Specialists

Independent consultants not listed previously.

K. T. Feldman Mechanical Engineering, Professor University of New Mexico Albuquerque, New Mexico	Research, testing, teaches short course, consultant
C. C. Silverstein Baltimore, Maryland	Consultant
D. K. Edwards, Professor Energy and Kinetics Department University of California at Los Angeles Los Angeles, California	Consultant, research
C. L. Tien, Professor Mechanical Eng. University of California Berkeley, California	Consultant, research
E. K. Levy, Mechanical Engineering Lehigh University	Research
J. K. Ferrell, Chemical Engineering North Carolina State University Raleigh, North Carolina	Research

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Heat Pipe Corporation of America  
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G. Yale Eastman

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**END**

**DATE**

**FILMED**

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